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PROJECT ADMINISTRATION DATA SHEET

[X] ORIGINAL [ ] REVISION NO. ______

Project No. E-25-646 (R-6069-0A0) GTRC/~~XXX~~ DATE 12/ 2 / 85

Project Director: J. T. Berry School/~~Lab~~ ME

Sponsor: Consolidated Aluminum Co.

Type Agreement: Research Project Agreement E-25-646

Award Period: From 11/6/85 To 3/5/86 (Performance) 3/5/86 (Reports)

Sponsor Amount:

	This Change	Total to Date
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Funded:	$ 19,875	$ 19,875

Cost Sharing Amount: $ N/A Cost Sharing No: N/A

Title: Study of Heat Transfer in Cooling Fluids Used in Casting Operations

ADMINISTRATIVE DATA

OCA Contact Ralph Grede x-4820

1) Sponsor Technical Contact:

2) Sponsor Admin/Contractual Matters:

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P.O. Box 164
Hannibal Ohio 43931
(614) 483-1341

Defense Priority Rating: N/A Military Security Classification: N/A

(or) Company/Industrial Proprietary: ______

RESTRICTIONS

See Attached N/A Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval – Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with Sponsor: However, no equipment is proposed.

COMMENTS:

Sponsor budget to be augmented by $1,988 for title to software.
(See Paragraph 11)

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SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

SP459 2

Date 4/7/86

Project No. E-25-646 (R-6069-0A0) School/Lab ME

Includes Subproject No.(s) None Indicated

Project Director(s) J.T. Berry GTRC / GIT

Sponsor Consolidated Aluminum Co.

Title Study of Heat Transfer in Cooling Fluids Used in Casting Operations

Effective Completion Date: 3/5/86 (Performance) 3/26/86 (Reports)

Grant/Contract Closeout Actions Remaining:

- [ ] None
- [x] Final Invoice or Final Fiscal Report
- [ ] Closing Documents
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FINAL REPORT

STUDY OF HEAT TRANSFER IN COOLING FLUIDS USED IN BILLET CASTING OPERATIONS

By

James G. Hartley
John Moosbrugger
Arno Louvo
John T. Berry

Prepared for

CONSOLIDATED ALUMINUM CORPORATION
P. O. Box 164
HANNIBALL, OHIO 43931

March 1986

GEORGIA INSTITUTE OF TECHNOLOGY
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
GEORGE W. WOODRUFF SCHOOL OF MECHANICAL ENGINEERING
ATLANTA, GEORGIA 30332

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Georgia Institute of Technology
A Unit of the University System of Georgia
George W. Woodruff School of Mechanical Engineering
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By

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INTRODUCTION

The assessment of the quenching capacity of cooling fluids used in certain aluminum alloy continuous casting operations is essential to the production of high quality billet. Central to present problems is the design, construction and operation of a device, together with its attendant data acquisition and computer software, to monitor changes in the cooling capacity of fluids used in this operation.

This report describes the design of the device, the methods used to estimate surface temperature and surface heat flux histories from measured quench specimen temperatures, the software developed to implement the analytical methods, and interfacing the quench measurements with a personal computer.

STATEMENT OF WORK

The original proposed program of research included the following:

(i) Design and construction of an experimental heat transfer apparatus. The apparatus will involve a small diameter cylinder of 1100 aluminum alloy in which is embedded a metal sheathed thermocouple.

(ii) The cylinder will be capable of being heated in a small vertical tube furnace to $1000^{o}F$. It will be quenched by immersion in samples of quenchant fluid placed beneath furnace.

(iii) To facilitate the construction of the device or quenchant probe, certain components will be specified by the research team and obtained directly by separate purchase by the sponsor. These components will be assembled into the quenchant probe at Georgia Tech.

(iv) The research team will undertake an analysis of heat transfer through the probe geometry, with a view to writing a computer program from which the surface temperature and the surface heat flux from the probe will be calculated. The data, which will be input to the personal computer to obtain this information, will be:

- time-temperature history in form of thermocouple output.
- specimen geometry and thermal property information.
- initial quenchant temperature.

The software developed will be well documented.

MATHEMATICAL ANALYSIS

The heat transfer to and through a long, solid cylindrical specimen can be determined by solving the transient conduction equation

$$\rho c \ \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rk \frac{\partial T}{\partial t}\right) \tag{1}$$

for the temperature distribution in the cylinder. The heat conduction problem is called a direct problem if, in addition to having the initial temperature of the specimen specified, the surface temperature history is also known. In such circumstances Eq. (1) can be solved using well-known analytical or numerical techniques. If the surface temperature history is unknown but the temperature history is known at some point within the specimen, the conduction problem is called an inverse problem. The inverse problem is ill-posed mathematically and the methods used to solve Eq. (1) in this instance are quite different from those employed in the solution to the direct problem.

In the quench test apparatus proposed in this work the centerline temperature history of a cylindrical specimen is to be measured rather than the surface temperature, so that an indirect conduction problem arises. Thus the succeeding discussion is concerned with analyzing the inverse problem in order to arrive at predictions of the surface temperature and surface heat flux histories from experimentally measured centerline temperature histories.

Simple Solution to the Inverse Problem

Since the thermal conductivity of metallic specimens varies with temperature, Eq. (1) is nonlinear and numerical methods are well-suited for its solution. The simplest approach to solving Eq. (1) subject to the following conditions

$$T(r,0) = T_i \text{ (initially uniform temperature)} \tag{2}$$

$$T(0,t) = T_c(t) \text{ (measured centerline temperature)} \tag{3}$$

$$\frac{\partial T}{\partial r}(0,t) = 0 \text{ (symmetry condition)} \tag{4}$$

is to assume that the centerline temperature is known exactly and to employ an implicit finite difference method [1]. If the centerline temperature history is exact, the surface temperature and surface heat flux histories can be predicted with extreme accuracy. However, when the centerline temperature history is measured experimentally, exact measurements are impossible owing to random measurement errors and other experimental uncertainties. As the simple implicit finite difference method is quite sensitive to these errors, surface temperature and surface heat flux histories predicted from experimental measurements of the centerline temperature display erratic trends.

Sequential Function Specification Method

One method of minimizing the influence of experimental errors on predicted temperatures and heat fluxes is called the sequential function specification (SFS) method [2]. This method was developed especially for inverse problems. The complete theory for the method is described in detail in Reference [2], and therefore the results are merely summarized in this section.

SFS attempts to smooth out random experimental errors by determining the temperature rise at future times owing to a step change in the heat flux at the surface of the specimen. This is accomplished with the use of so-called sensitivity coefficients. In the present work the temperature distribution as well as the sensitivity coefficients are determined numerically using an implicit finite difference method. The variable thermal properties are treated in a quasi-linear manner, i.e. the properties evaluated at temperatures corresponding to the beginning of a time step are assumed to remain unchanged during that time step. They are, however, updated at the beginning of each time step.

To implement the SFS method the conduction equation and its boundary conditions are written in the form of a direct problem as follows:

$$\rho c \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(kr \frac{\partial T}{\partial r}\right) \tag{5}$$

$$\frac{\partial T}{\partial r} = 0 \qquad \text{at } r = 0 \tag{6}$$

$$-k \frac{\partial T}{\partial r} = q''(t) \qquad \text{at } r = R \tag{7}$$

$$T(r, t_{M-1}) = f(r) \tag{8}$$

Equation (8) is a statement that the temperature distribution is known at some instant of time denoted by t_{M-1}. Equations (5) through (8) are then used to march the solution forward one time step to time t_M. Of course, the heat flux at the surface of the specimen, $q''(t)$ in Eq. (7), is unknown and is to be determined using SFS.

The sensitivity coefficient, Z_k, is defined as

$$Z = \frac{\partial T}{\partial q''} \tag{9}$$

and therefore satisfies the following:

$$\rho c \ \frac{\partial Z}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial Z}{\partial r}\right) \tag{10}$$

$$\frac{\partial Z}{\partial r} = 0 \quad \text{at } r = 0 \tag{11}$$

$$-k\,\frac{\partial Z}{\partial r} = 1 \quad \text{at } r = R \tag{12}$$

$$Z(r_1, t_{M-1}) = 0 \tag{13}$$

When Eqs. (5) through (8) and Eqs. (10) through (13) are written in finite difference form, a set of algebraic equations of the following form results:

$$\begin{bmatrix} b_1 & -a_1 & & & & \\ -c_2 & b_2 & a_2 & & & \\ & \cdot & \cdot & \cdot & & \\ & & \cdot & \cdot & \cdot & \\ & & & -c_{N-1} & b_{N-1} & -a_{N-1} \\ & & & & -c_N & b_N \end{bmatrix} \begin{Bmatrix} S_1^M \\ S_2^M \\ \cdot \\ \cdot \\ S_{N-1}^M \\ S_N^M \end{Bmatrix} = \begin{Bmatrix} d_1^S \\ d_2^S \\ \cdot \\ \cdot \\ d_{N-1}^S \\ d_N^S \end{Bmatrix} \tag{14}$$

where S denotes temperature, T, and sensitivity coefficient, Z, for Eqs. (5) through (8) and Eqs. (10) through (13), respectively. All coefficients other than a_i, b_i and c_i in the coefficient matrix of Eq. (14) are zero.

The coefficients in Eq. (14) are defined as follows:

$$a_1 = 2\lambda k_{1+} / (\rho c)_1 \tag{15.1}$$

$$c_1 = 0 \tag{15.2}$$

$$a_i = \lambda (kr)_{i+} / (\rho c r)_i \quad ; \quad i = 2, \ldots, N-1 \tag{15.3}$$

$$c_i = \lambda (kr)_{i-} / (\rho c r)_i \quad ; \quad i = 2, \ldots, N-1 \tag{15.4}$$

$$a_N = 0 \tag{15.5}$$

$$c_N = 2\lambda(kr)_{N-} /(\rho cr)_N \tag{15.6}$$

$$b_i = a_i + c_i \qquad ; i = 1,\dots, N \tag{15.7}$$

$$d_i^S = s_i^{M-1} \qquad ; i = 1,\dots, N-1 \tag{15.8}$$

$$d_N^S = s_n^{M-1} - c_N \Delta r g^S/(kr)_{N-} \tag{15.9}$$

where the single subscripts denote nodal location in the finite difference grid ($i = 1$ corresponds to $r = 0$ and $i = N$ corresponds to $r = R$), $i+$ signifies that average values based upon nodes i and $i + 1$ should be used, $i-$ signifies that average values based upon nodes i and $i - 1$ should be used, and λ and g^S are defined as

$$\lambda = \Delta t/(\Delta r)^2 \tag{16}$$

and

$$g^S = \begin{cases} q''^M & \text{for } S = T \\ 1 & \text{for } S = Z \end{cases} \tag{17}$$

The symbols Δt and Δr denote time step size and radial location step size, respectively.

Since the surface heat flux is unknown, the SFS method first uses an assumed value of q'' (denoted by q^*) at the beginning of each time step and predicts the centerline temperatures, T_j^*, and centerline sensitivity coefficients, Z_j^* for k future time steps by solving Eq. (14) repeatedly, k times. The predicted temperatures, T_j^*, corresponding to the experimentally measured values (T_c), and the sensitivity coefficients, Z_j^*, are used to estimate the true heat flux value according to the following relation [2]

$$q''^M = q^* + \sum_{j=1}^{k} (T_c^{M+j-1} - T_j^*) K_j \quad (18)$$

where

$$K_j = Z_j^* / \sum_{j=1}^{k} Z_j^{*2} \quad (19)$$

is called the gain coefficient.

General Solution Algorithm

The following algorithm is used to implement the SFS method on the personal computer:

1. Assume an arbitrary value of q^* (a value of 0.1 is used in the program listed in Appendix B) which is assumed to remain constant over the time interval from t^{M-1} to t^{M+k-1}.
2. Set $j = 1$.
3. Using the assumed q^* value, solve for T_i^{M+j-1}, $i = 1, \ldots, N$.
4. Set $T_j^* = T_N^{M+j-1}$.
5. Solve for Z_i^{M+j-1} $(i = 1,\ldots,N)$ from Eq. (14) with $S = Z$.
6. Set $Z_j = Z_N^{M+j-1}$.
7. Repeat steps 3 through 6 for $j = 2,\ldots, k$. ($k = 3$ is used in the program listed in Appendix B)
8. Solve Eq. (18) for q''^M. This is the best estimate of the surface heat flux during the interval of time from t_{M-1} to t_M.
9. Increment M.
10. Repeat steps 1 through 8 until t_M reaches the desired maximum value.

Corrections for Finite Specimen Length

The specimen used in the quench test apparatus has a finite length, L_F, whereas the analysis presented in the preceding sections assumes that the specimen has an infinite length. This means that computed surface heat flux values will be higher than the actual values.

The assumption of an infinite length was made in order to simplify the personal computer program and to significantly reduce the required computation time. However, estimates of the surface heat flux for the actual specimen are obtained as described below.

For a small diameter specimen, such as the one used in the quench test apparatus, the difference between the centerline temperature and the surface temperature is relatively small. Therefore, we can assume that the specimen is nearly isothermal at any instant of time, and the surface heat flux can be determined from

$$q'' = - \rho c\left(\frac{V}{A} \right) \frac{dT}{dt}$$

where (V/A) is the ratio of the volume and surface area of the specimen, and $\frac{dT}{dt}$ is the measured centerline temperature history.

Using subscript I to denote the inifinite cylinder and subscript F to denote the cylinder of finite length, we obtain

$$q''_I = - \rho c\left(\frac{V}{A} \right)_I \frac{dT}{dt} \tag{20}$$

and

$$q''_F = - \rho c \left(\frac{V}{A} \right)_F \frac{dT}{dt} \tag{21}$$

Combining Equations (20) and (21) we find that

$$q''_F = q''_I \frac{(V/A)_F}{(V/A)_I} \quad . \tag{22}$$

or

$$q''_F = q''_I \left(\frac{\pi R^2 L_F}{2\pi R^2 + 2\pi R L_F} \right) \left(\frac{2\pi R L_I}{\pi R^2 L_I} \right)$$

$$= q''_I/(1 + R/L_F) \tag{23}$$

Thus surface heat flux values computed using Eq. (1), which assumes an infinite cylinder, are corrected in accordance with Eq. (23) in order to obtain an estimate of the surface heat flux for the quench specimen having a finite length.

EXPERIMENTAL APPARATUS AND DATA ACQUISITION SYSTEM

The experimental apparatus used for the immersion quenching tests is detailed in Figure 1. The system consists of: (1) a hinged, tube-type furnace (typically used for high temperature, mechanical testing) which is mounted on a frame, (2) a steel sleeve and set-screw which is also attached to the frame and which serves as a sliding mechanism for delivering the specimen from the furnace chamber to the quench bath, (3) a quench bath situated directly beneath the furnace chamber, (4) a specimen/thermocouple/delivery tube assembly, (5) a furnace controller and (6) a data acquisition system.

The furnace used was a Lindberg Hevi-Duty Type 54331-A (115/230 Volts, 1650 Watts; Maximum Temperature 1850^{o}F) with a Lindberg Type 59344 controller (115/208/230 Volts, 35 Watts) which uses a platinel no. 2 control thermocouple. The control thermocouple hot junction is located at the halfway point between the top and bottom of the furnace chamber.

The specimen/thermocouple/delivery tube assembly is detailed in Figure 2. The assembly consists of: (1) a 48 inch long, type K thermocouple which has a grounded junction and is shrouded in 1/16 inch diameter, type 306 stainless steel tubing (Omega Engineering Inc., catalog No. CASS-116G-12), (2) a 1/4 inch diameter stainless steel delivery tube which encapsulates the thermocouple probe and which is affixed to the thermocouple connector and (3) a 1/2 inch diameter aluminum (1350 alloy supplied by Consolidated Aluminum) specimen which is counter-bored and threaded to allow a rigid connection to the delivery tube. The hot junction end of the thermocouple probe seats in a concentric bore with a diameter which allows the minimum amount of clearance possible. The dimensions of the delivery tube and specimen counter-bore are specified so that the thermocouple probe is loaded in compression when the assembly is completed. This ensures a continuous contact between the aluminum

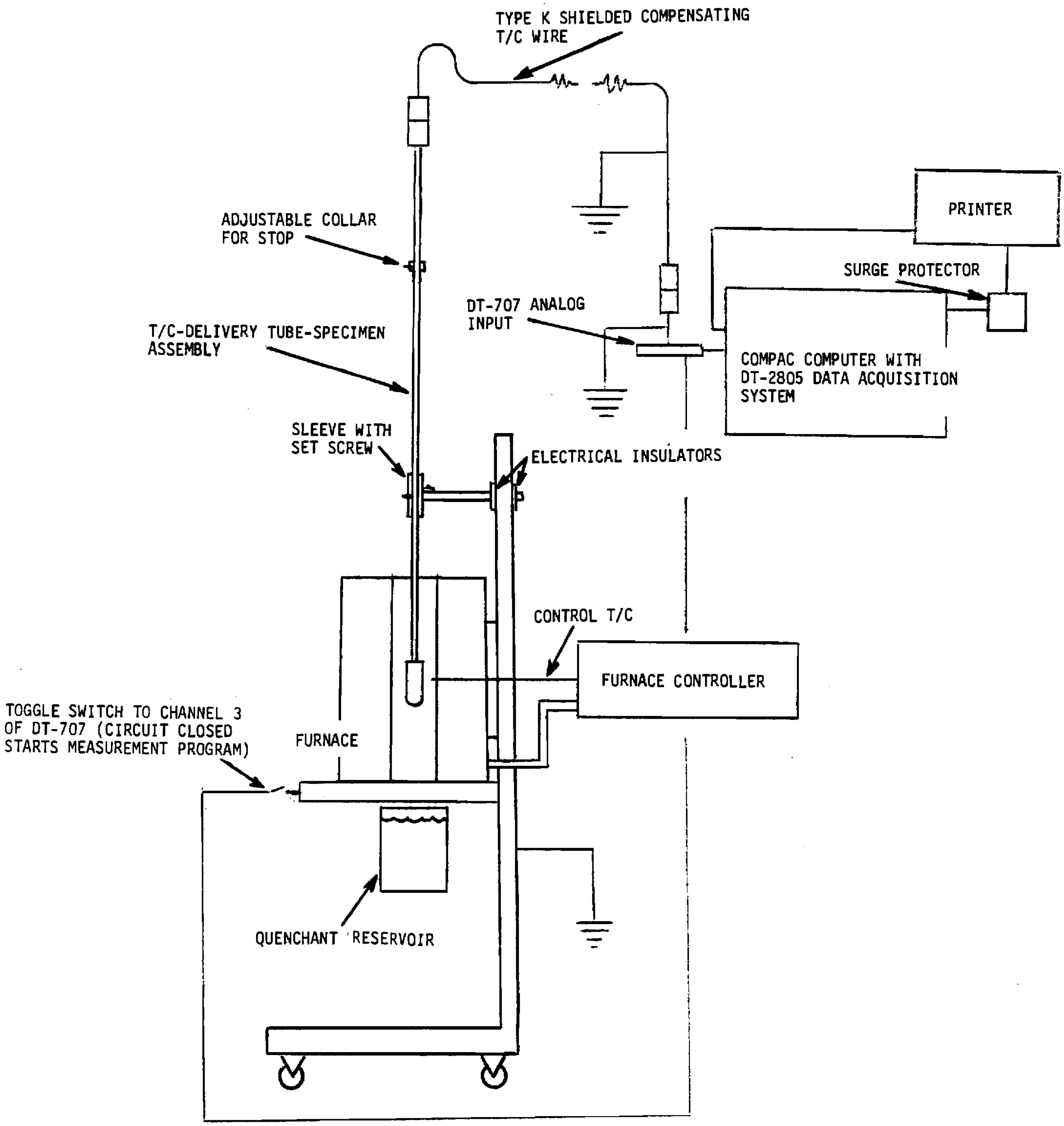

Figure 1. Experimental Apparatus and Data Acquisition System.

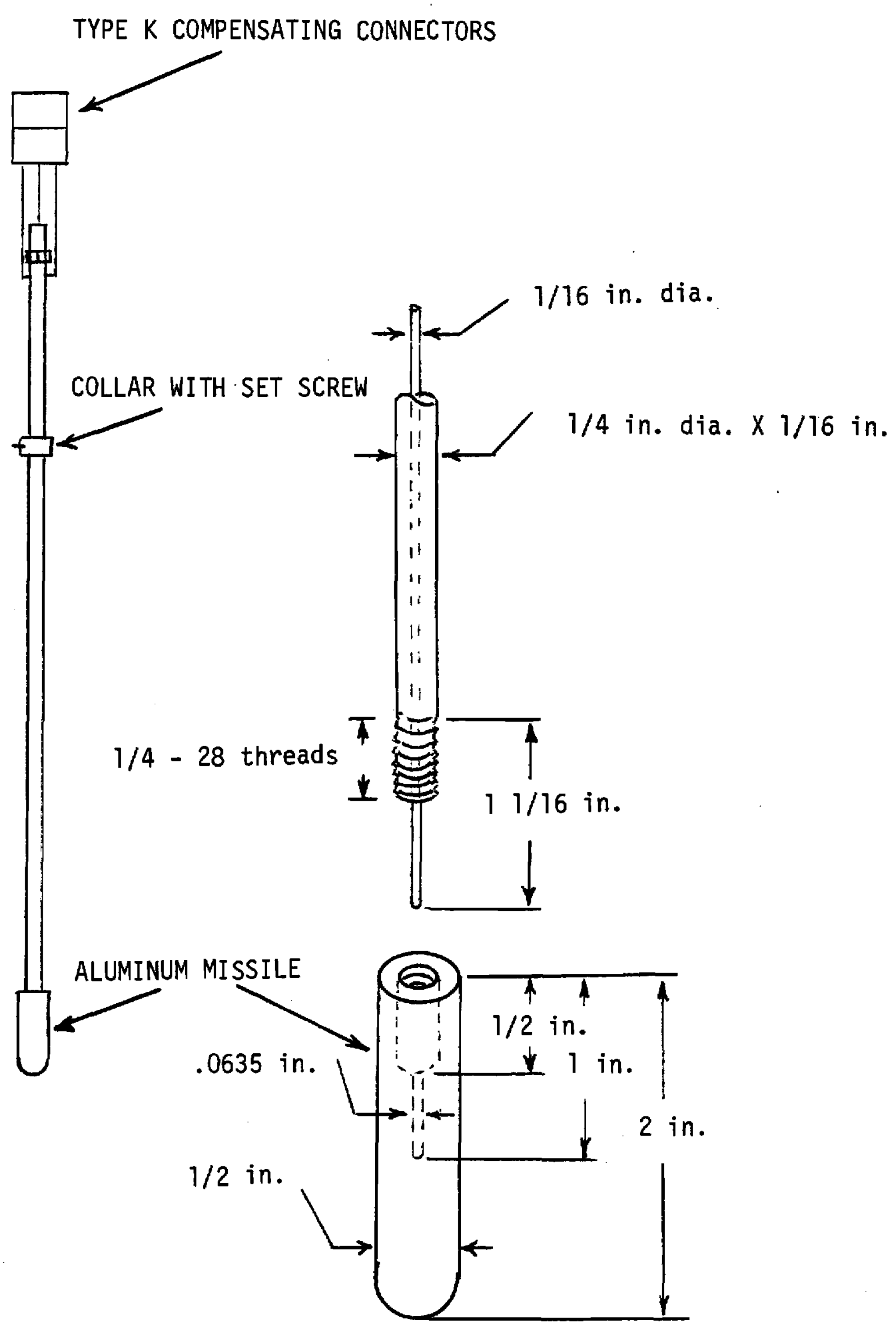

Figure 2. Specimen/Thermocouple/Delivery Tube Assembly.

specimen and the thermocouple hot junction. Although this mechanical connection has the disadvantage of possible thermal contact problems, if offers the advantages of simplicity and flexibility in that specimens and thermocouples can be readily replaced when necessary and the assembly does not require the special fabrication facilities that would be necessary for a metallurgical bond. The thermocouple is connected to the analog input of the data acquisition system with type K compensating connectors and lead wires.

The data acquisition system consists of: (1) an analog input board (Data Translaton DT-707) designed specifically for thermocouple input signals and a Data Translation DT-2805 data acquisition system. This system allows several low level bipolar input voltage ranges depending on the gain setting, which is software programmable to be one of four levels, and the resolution is 12 bits (See DT2801 Series User Manual for details), (3) a Compaq personal computer and Epson model FX-85 printer and (4) a surge protector which filters noise from 115 VAC power sources and protects against voltage surges. The software required to operate the data acquisition system, which has been tailored specifically to the present application, is detailed in later a section of this report.

Special care should be exercised to minimize external noise pick-up while using the data acquisition system. Because the system is constructed primarily of metallic components, it is important to electrically isolate these components from the thermocouple as much as possible. Thus, the connection between the sleeve and delivery tube mechanism and the mounting frame should provide electrical insulation between the frame and the mechanism. Also, as shown in Figure 1, the frame should be grounded and shielded thermocouple lead wires should be used with their respective shields also grounded. These steps will ensure a minimum amount of error in temperature measurements owing to external noise while performing a test.

Test Procedure

The test procedure consists of heating the specimen to a steady, uniform quench temperature and then loosening the set screw holding the delivery tube while simultaneously initiating a program for data acquisition and storage. The specimen then drops into the quench bath and the centerline temperature history of the specimen is recorded and stored on a floppy disk. This data can then be used as input for an analysis program which computes the specimen surface temperature and heat flux histories. The results can be plotted in a variety of formats which are user-selectable. The details of the test procedure, use of data analysis software, and options available to the user are given in the User Guide section of this report.

SAMPLE TEST RESULTS

Test results as well as surface temperature and surface heat flux histories calculated from the INVERSE program (Appendix B) can be displayed on the video screen of an IBM PC compatible personal computer using program CONSAL (Appendix C). This program is completely interactive and user-friendly.

The information on the opening screen is shown in Figure 3. After the user strikes any key the main menu, shown in Figure 4, is displayed. From this menu the user may select any one of six plotting options. He may also choose to reenter the analysis or measurement programs (INVERSE or QUENCH, respectively) or terminate the CONSAL program.

Sample graphical output is shown in Figures 5 through 8. For example, selecting option 2 from the main menu causes the calculated surface temperature history (^{o}F vs. sec) to be displayed (See Figure 5). Selecting option 4 causes the calculated heat flux history (Btu/ht $\cdot$ ft^2 $\cdot$ ^{o}F vs sec) to be displayed (See Figure 6). Selecting option 5 results in a plot of calculated surface heat flux versus surface temperature (Btu/hr $\cdot$ ft^2 $\cdot$ ^{o}F vs. ^{o}F) as shown in Figure 7. Figure 8, obtained by selecting option 6, is a log-log plot of surface heat flux versus the difference between surface temperature and quenchant temperature (Btu/hr $\cdot$ ft^2 $\cdot$ ^{o}F) vs. ^{o}F).

The results shown in Figure 7 are typical results obtained by quenching the aluminum specimen in pure water. When additives are present in the water their qualitative influence on the surface heat flux can readily be evaluated by comparing the heat flux versus surface temperature plot to the results obtained with the same specimen quenched in pure water.

** QTAP **

Quench Test Analysis Program

prepared for

Consolidated Aluminum Corporation

by

Georgia Institute of Technology

School of Mechanical Engineering

Figure 3. Opening Screen Produced by CONSAL Program.

```
              ** QTAP Plot Options **

    The results may be plotted in one of the following forms:

1 - Centerline temperature history

2 - Surface temperature history

3 - Centerline and surface temperature histories

4 - Surface heat flux history

5 - Surface heat flux vs. surface temperature

6 - Surface heat flux vs. surface temperature difference

7 - ANALYZE a new quenching curve (Interpreter BASIC)

8 - MEASURE a new quenching curve (Interpreter BASIC)

Q - QUIT

            ***                          ***
```

Figure 4. Main Menu for CONSAL Program.

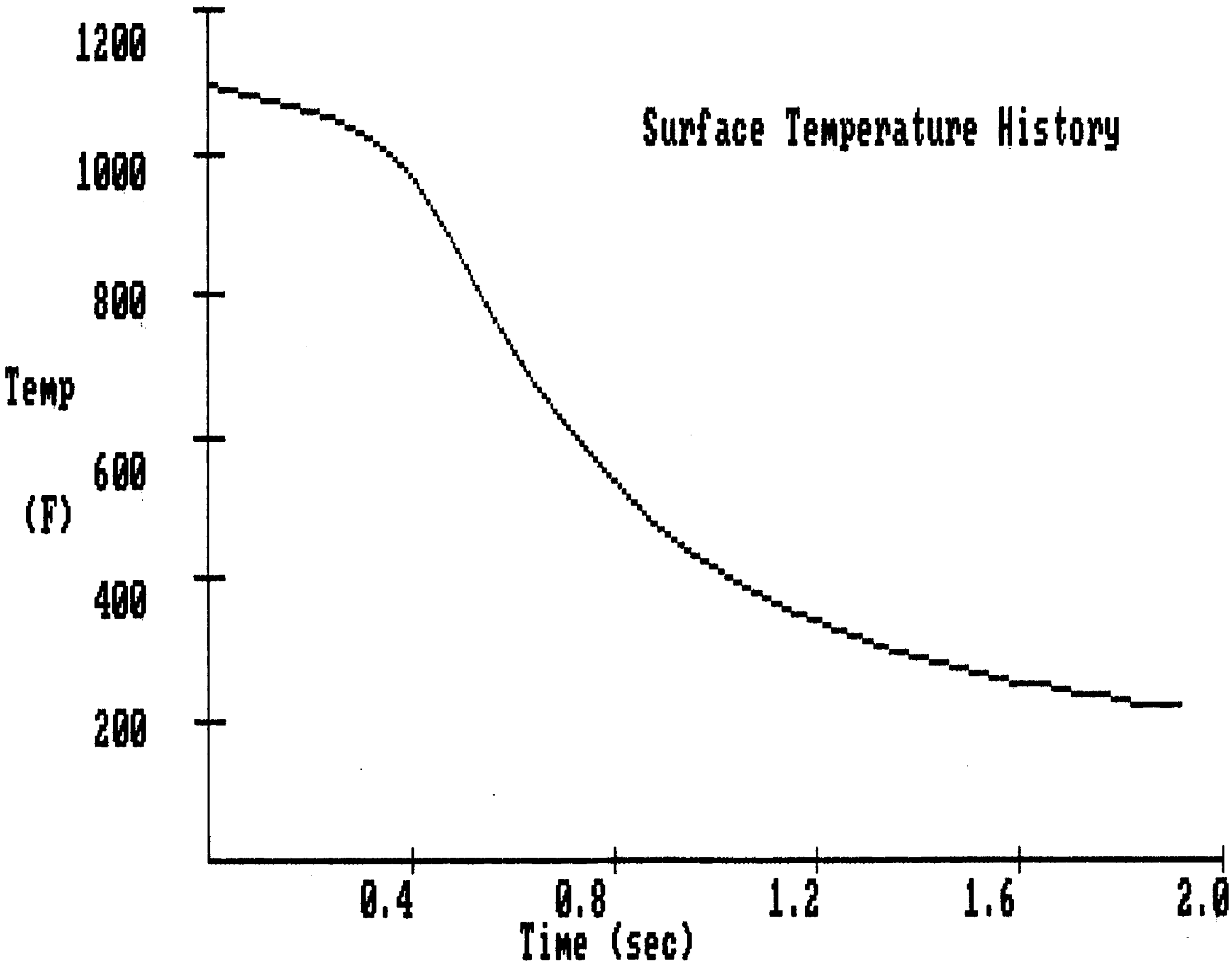

Figure 5. Sample Plot of Calculated Surface Temperature History.

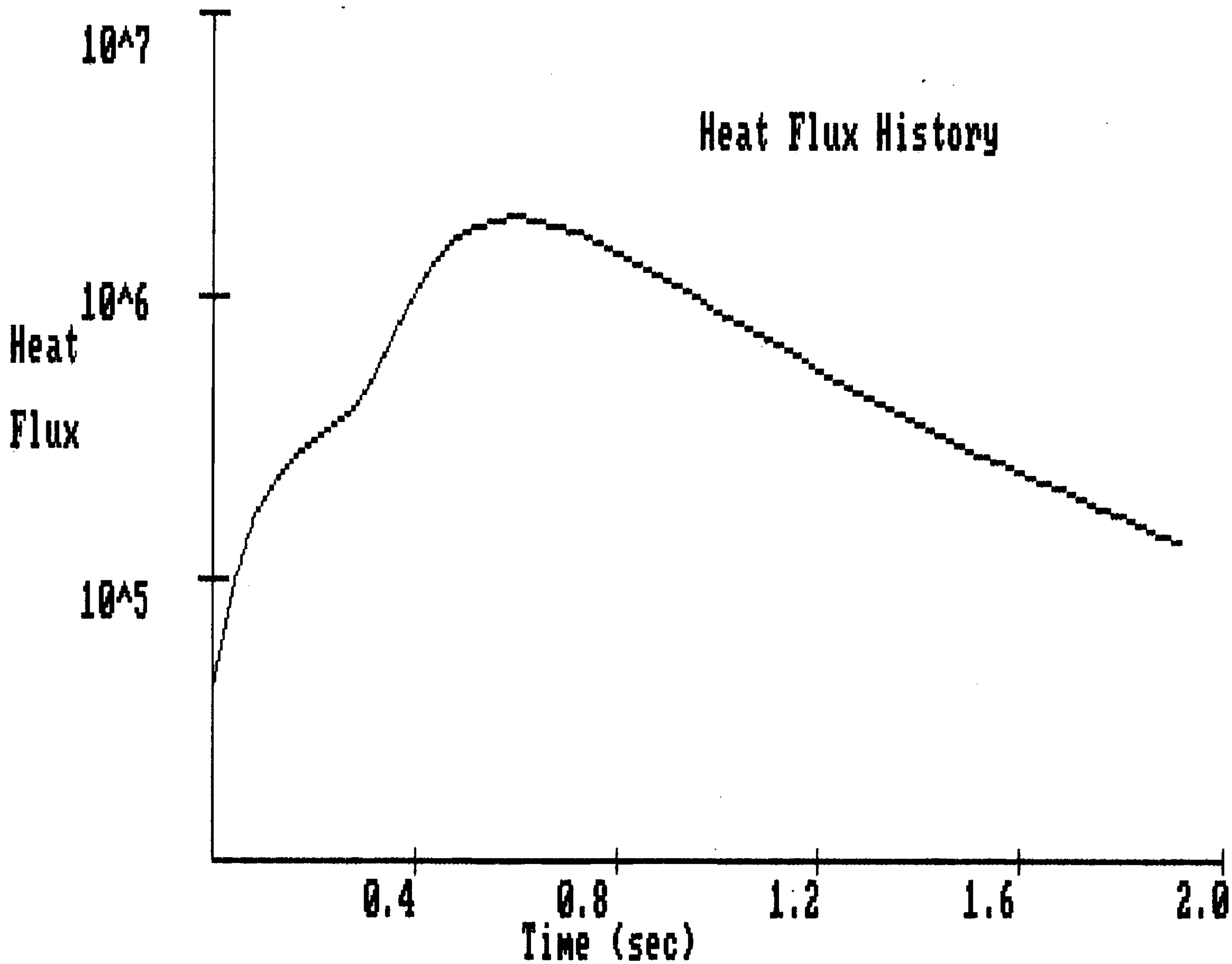

Figure 6. Sample Plot of Calculated Surface Heat Flux History.

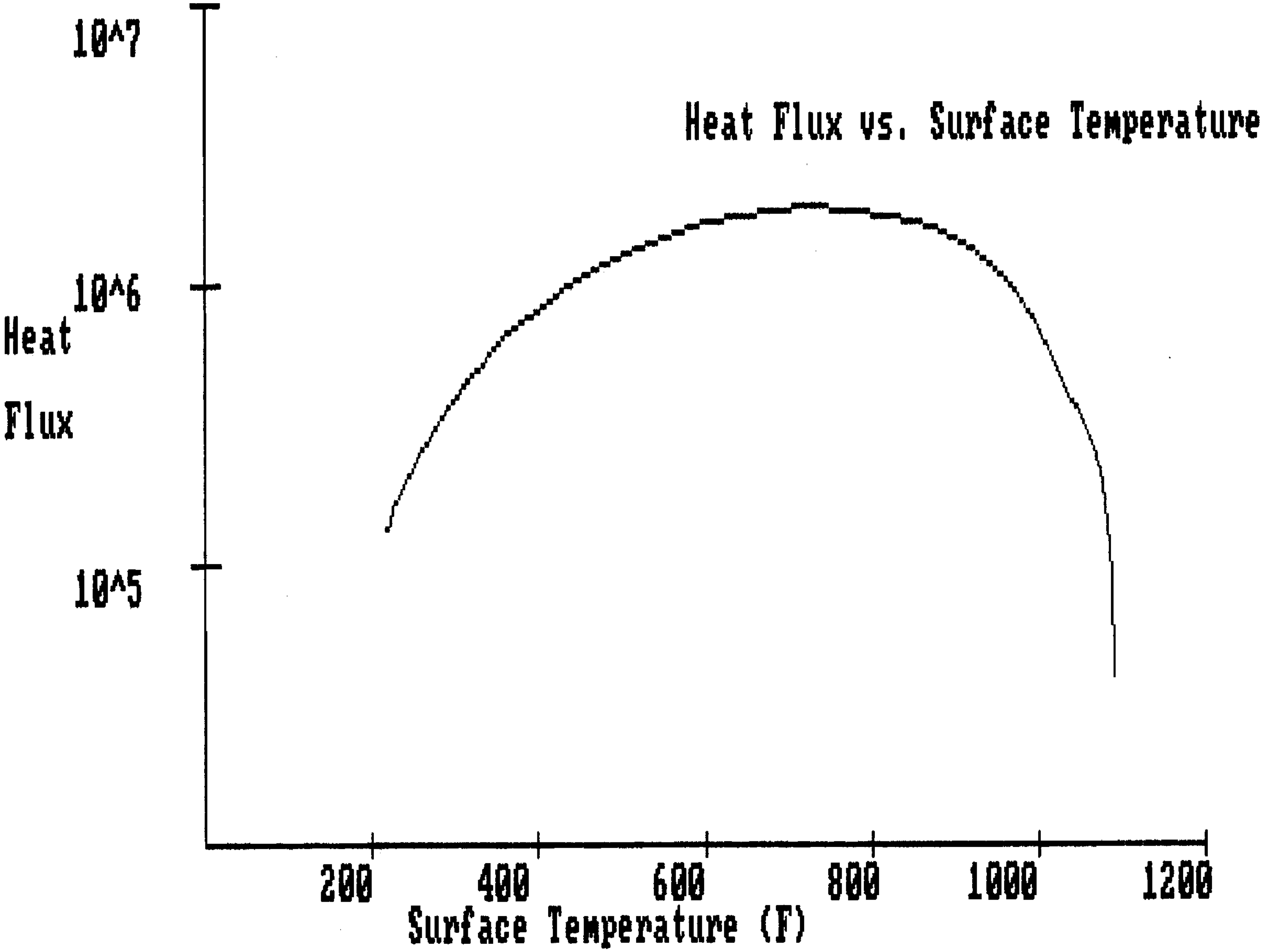

Figure 7. Sample Plot of Surface Heat Flux Versus Surface Temperature.

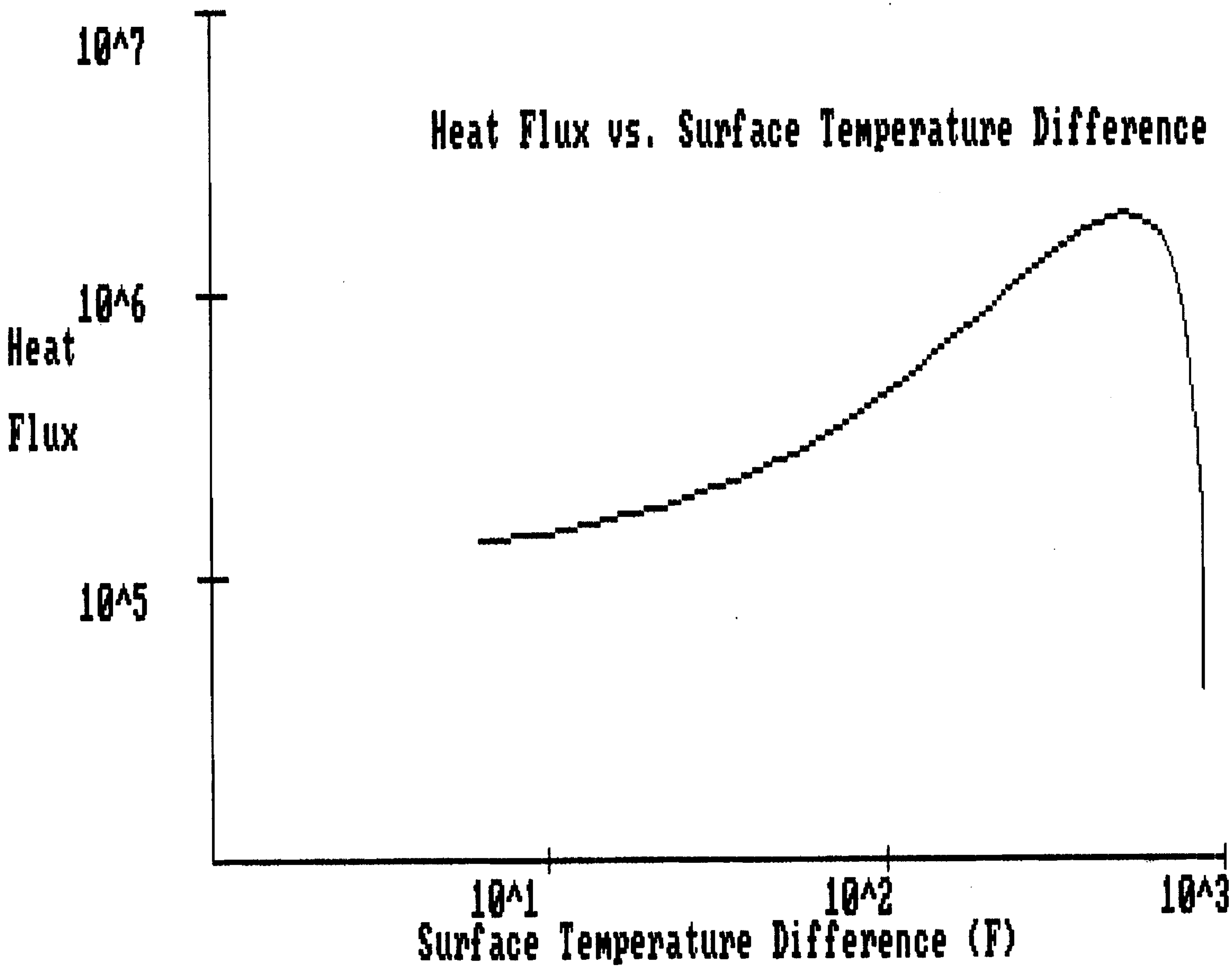

Figure 8. Sample Plot of Surface Heat Flux Versus Surface Temperature Difference ($T_{surface}$ - $T_{quenchant}$).

SUMMARY

This research work has led to the development of an accurate, reliable and relatively rapid technique for determining the surface heat flux and surface temperature histories of a cylindrical specimen during a quench test. The data acquisition and data reduction have been automated and implemented in a Compaq computer, and software has been developed for displaying the results graphically in a variety of formats.

The computer software is written in BASIC and the programs are well-documented and user-friendly. The measurement and analysis system provides a reliable means of evaluating and comparing the influence of water quality on the heat transfer characteristics of the quench water.

REFERENCES

1. B. Carnahan, H. A. Luther, and J. O. Wilkes, Applied Numerical Methods, John Wiley and Sons, New York, 1969.

2. J. V. Beck, B. Blackwell, and C. R. St. Clair, Inverse Heat Conduction, John Wiley and Sons, New York, 1985.

LIST OF SYMBOLS

a_i, b_i, c_i, d_i	Coefficients defined in Eq. (15)
c	Specific heat, Btu/lb ^oF
g	Parameter defined in Eq. (17)
k	Thermal conductivity, Btu/hr ft ^oF
L	Length of specimen, ft
q"	Heat flux, Btu/hr ft^2
r	Radial coordinate, ft
R	Outside radius of specimen, ft
s	Generalized dependent variable
t	Time, hr
T	temperature, ^oF
V	Volume, ft^3
Z	Sensitivity coefficient, ^oF hr ft^2/Btu

Greek Symbols

λ	Parameter defined in Eq. (16)
ρ	Density, lb/ft^3

Subscripts

F	Cylinder of finite length
I	Cylinder of infinite length
i	nodal location (i = 1, ..., N)
i+	average value for nodes i and i+1
i-	average value for nodes i and i-1

Superscripts

M	Time step designation
s	Denotes generalized dependent variables

APPENDIX A

BASIC Program Listing for Date Acquisition Program
(QUENCH)

APPENDIX B

BASIC Program Listing for Data Analysis Program
(INVERSE)

APPENDIX C

BASIC Program Listing for Graphical Display Program
(CONSAL)

APPENDIX D

User Guide to QUENCH 1.0 Software

APPENDIX E

Thermal Properties Used in Data Analysis Program

The following expressions are used to evaluate the thermal properties in the data analysis program listed in Appendix B.

$$k(T) = 0.0333 + 4.075 \times 10^{-6} T\ (^{o}F); \quad BTU/s \cdot ft \cdot {}^{o}F \tag{1}$$

$$\rho c(T) = 34.51 + 0.01225\ T(^{o}F)\ ; \ BTU/ft^{3} \cdot {}^{o}F \tag{2}$$

Equation (1) is a curve fit of data from curve 4, pp. 905-907, for thermal conductivity of aluminum/iron alloys in Volume 1 of Reference E-1. Equation (2) is a curve fit of data derived from Curve 4, pp. 1-5, for specific heat of aluminum in Volume 4 of Reference E-1.

Reference E-1: Touloukian, Y.S. and C.Y. Ho, Eds., Thermophysical Properties of Matter, Plenum Press, New York, 1972.